Recent Quench Performance of Fermilab High Gradient Quadrupole Short Models for the LHC Interaction Regions

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Abstract

Fermilab and LBNL are in the midst of a superconducting magnet R&D program to test and optimize the design of quadrupoles to be used in the LHC Interaction Region inner triplets. The magnets are required to deliver a 205 T/m gradient across a 70mm aperture. Five short models have been fabricated and four of them have been tested. This paper describes the pertient design details and reports the test results of the recent model.

1. Introduction.

The LHC Interaction Region inner triplets consist of four 70mm single aperture quadrupoles (MQX), which have to provide a nominal field gradient of 205 T/m at collision optics and 215 T/m at injection. Fermilab and LBNL are developing half of quadrupoles based on these requirements for the LHC interaction points, with KEK developing the other half based on a different design [1].

A series of 2m long model magnets (HGQ) is being built now at Fermilab to test and optimize the design and assembly method, before proceeding to the construction of a full length prototype magnet. The baselin design, and test results of the the first 3 models of this series have been reported elsewhere [2,3,4]. This paper summarizes the design optimization, and quench performance of the most recent model magnet.

2. Design optimization.

The HGQ01-03 training results can be summarized as follows. All models demonstrated long and slow training at both 4.5K and 1.9K temperatures. The maximum achieved field gradient of ~215 T/m is close to the nominal injection field gradient but it is much lower than the magnet short sample limit of 250 T/m. Through all three magnets, the quench locations are dominantly in the coil ends and the body to end transition region. Analysis of the HGQ01-03 results showed that the quench performance is associated with a) insufficient and non-uniform coil end and end body transition prestress; b) low coil end rigidity; c) significant difference in the Ultem-part/coil thermal contraction coefficient and d) insufficient longitudinal stability of the collar structure.

Model HGQ05 included a set of changes which addressed the issues raised by previous models. The changes focused on the optimization of azimuthal prestress in the body/end transition, improvement of radial and longitudinal end support, better matching of the curing pressures and properties of the inner and outer coils, and improved stability of the collar structure.

The most important of the changes from the baseline design included on HGQ05 are:

- Use of G10 as end part material
- Recure of inner coil at higher pressure, resulting in a higher inner layer modulus and more uniform inner/outer coil mechanical properties
- A continuous body/end transition, including elimination of key extension
- Welded 75mm collar packs, including pole filler pieces
- Aluminum end can assemblies over both ends
- Attachment of the end cans to the end plate, which ensures contact between the coil ends and end plates and stretches the coil straight section after cooldown

3. Test results and discussion

Magnets were tested at the Fermilab Vertical Magnet Test Facility (VMTF) [3] in normal and super-fluid liquid Helium in the temperature range of 1.8-4.5 K. During quench performance study about 50% of stored energy were extracted and dissipated in dump resistor. Each magnet was instrumented with 96 voltage taps installed on the inner and outer coils. Pole turns and turns around wedges were instrumented with four voltage taps each to distinguish between the coil end and straight section quenches.

3.1. Mechanical measurements.

Coil azimuthal stresses and longitudinal end force measurements were made at room temperature during fabrication and during cold test in each excitation cycle. The results are summarized in Table I.

Table I
MECHANICAL MEASUREMENT SUMMARY

HGQ	01	02	03/03A	05
Azimuthal prestress 300K				

inner layer, MPa outer layer, MPa	67 72	73 94	187/199 97/113	99 55
Azimuthal prestress 1.9K inner layer, MPa outer layer, MPa	 38 58	 76 84	 173/175 102/105	 ? 49

According to strain gauge measurements the azimuthal coil prestress in magnet body was sufficient. No unloading of the coils was observed at the highest operating currents reached by these magnets. Coil deformation by Lorentz force was elastic in operation current range.

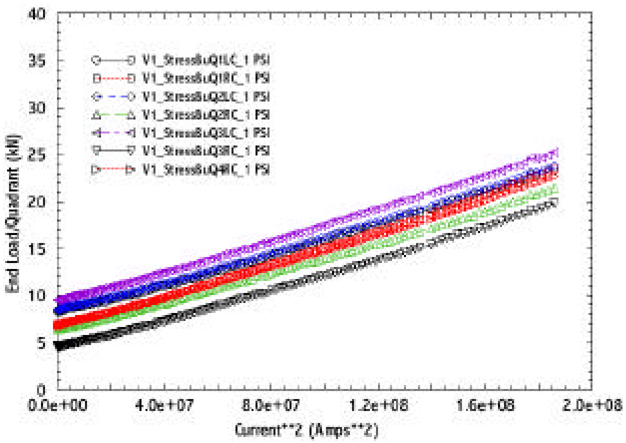

Figure shows a typical longitudinal coil force measurement for magnet HGQ05. Ther was end longitudinal prestress on both ends after cooling down. The slope of end force with current represents about 25% of the calculated Lorentz force.

3.2. Magnet training.

Training results for this magnet at 4.5 K and 1.9 K obtained in first thermal cycle are presented in Figure 2.

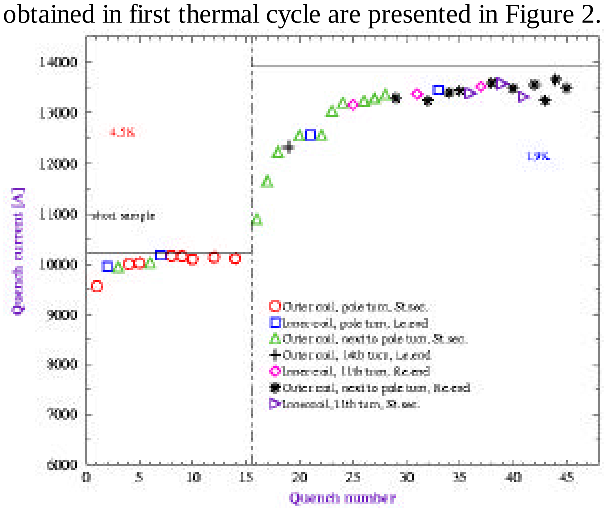

Figure 2. HGQ05 training results.

As can be seen a dramatic improvement of the magnet training at both temperatures was observed. At 4.5 K after short training the estimated short sample limit has been achieved. At 1.9 K only two quenches required to reach the nominal operation current. Then when quench current reached 95% of the short sample limit the training rate slowed dawn and the erratic quenches occurred. Maximum gradient achieved was ~240 T/m which is well above nominal field gradient. The magnet training memory will be studied in the second thermal cycle.

3.3. Ramp rate sensitivity.

Ramp rate dependence of magnet quench current vs current ramp rate measured for HGQ05 at 1.9 K is shown in Figure 3. One can see two regions on this curve: flat, ramp rate independent region at low current ramp rates and region with monotonic decrease of quench current with the increase of current ramp rate. As it was found high ramp rate quenches were determined by AC losses in the cable near inter layer splices.

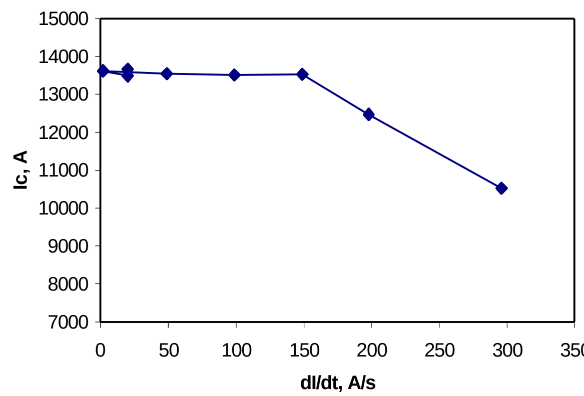

Figure 3. HGQ05 ramp rate dependance at 1.9 K.

Summary of magnet ramp rate sensitivity and coil curing temperature for HGQ01-03 and 05 is reported in Table III.

Table III
RAMP RATE SENSITIVITY

Model number	Coil curing temperature	Ic(150 A/s), A	Ic(300 A/s), A
HGQ01	135 ^{O}C	11752	10965
HGQ02	190 ^{O}C	-	11335
HGQ03	195 ^{O}C	11756	11298
HGQ05	130 ^{O}C	13531	10519

For all magnets the quench current ramp rate sensitivity is low for studied current ramp rates up to 300 A/s. This ramp rate by order of magnitude higher than the nominal LHC current ramp rate. It does not depend on the coil curing temperature (interstrand resistance in the cable still quite high). It is determined by AC losses in the cable and its cooling conditions near inter layer splices.

3.4 Temperature dependance of quench current.

Temperature dependance of magnet quench current is summarized in Figure 4. This dependence was measured after the completion of magnet test at 1.9 K. As it can be seen it is practically flat for the HGQ01-03 at low temperatures. This indicates that it is determined by the mechanically limited quenches. Then when temperature approached to 4.0-4.5 K magnets reached the short sample limit. For HGQ05 a monotonic decrease of quench current with the temperature increase was observed at temperatures above 1.9 K. It can be seen that after training in superfluid helium all magnets reached its short sample limit at 4.5 K. It confirms that max quench current reached during training of HGQ01-03 was not conductor limited. Magnet temperature margin at nominal current is about 2.3 K as predicted by calculations.

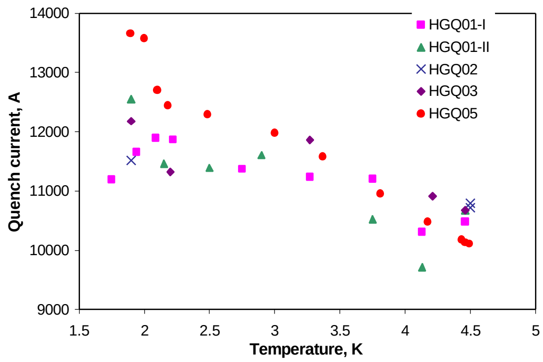

Figure 4. HGQ01-05 temperature dependance

4. Conclusions

Four High Gradient Quadrupole short models for the LHC IR have been fabricated and tested at Fermilab. Significant improvement in magnet training at 4.5 and 1.9 K was achieved in last model (HGQ05) as a result of the optimization of design details of magnet support structure. Magnet test in second thermal cycle is being continued. Although the results obtained demonstrate that the magnet design can provide the required quench performance some further optimization is desirable. Short model R&D program in being re-evaluated based on the program goals and results achieved. Two additional short models are included in the program to complete design optimization.

5. Acknowledgments

Authors would like to thank engineers and technicians of Fermilab Technical Division for the contribution to this work.

References

[1] Y. Ajima et al., "Development and Test Results of a Low Beta Quadrupole Model for the Large Hadron Collider", EPAC 1998.

[2] R. Bossert et al., "Development of a High Gradient Quadrupole for the LHC Interaction Regions", IEEE Trans. on Applied Superconductivity, Vol. 7, No 2, June 1997, p. 751.

[3] R. Bossert et al., "Fabrication of the First Short Model of High Gradient Quadrupole for the LHC Interaction Regions", MT-15, Beijing, October 1997.

[4] J. Kerby et al., "Design, Development and Test of 2m Quadrupole Model Magnets for the LHC Inner Triplet", presented at Applied Superconductivity Conference (ASC'98), Palm Desert (CA), September 1998.

[5] M. J. Lamm et al., "A new facility to test Superconducting Accelerator Magnets", PAC'97, Vancouver, Canada, 1997.